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The report describes the work done during the three-year period of the Graduate Fellowship in Applied Mathematics funded by the U.S. Army Research Office and summarizes the dissertation research plan of the incumbent fellow.

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FINAL TECHNICAL REPORT

Donald E. McClure

31 October 1989

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FELLOWSHIP IN APPLIED MATHEMATICS

1 Introduction

The fellowship contract was awarded to Brown University in 1986 for the purpose of providing three years of support for a graduate student in the Division of Applied Mathematics. The specific area of research that was targeted for support in the proposal and in the resulting contract was in association with the ARO-supported research team in the Division working on applications of probability and statistics to problems in image analysis, pattern recognition, and inference for complex systems.

In an attempt to realize a genuine incremental effect from use of the fellowship, the Principal Investigator placed the highest priority on trying to attract a new student to the program, rather than using the award to supplant other forms of support already provided for continuing students.

The fellowship was offered to Christopher S. Raphael, an applicant to the Division's Ph.D. program in 1986. Mr. Raphael accepted the offer and matriculated in the Division's Ph.D. program in September 1986, when the period of performance for the fellowship contract commenced. Mr. Raphael entered the Ph.D. program with excellent credentials in Computer Science and Mathematics from his undergraduate work at the University of California at Santa Cruz. As we suggested in our original proposal, our nomination of Mr. Raphael for the fellowship was reviewed by the Associate Dean of the

Graduate School to assure that it met the high standards of the Graduate School for the award of prize fellowships.

2 Year I

Christopher Raphael identified medical image processing problems as an area of likely interest for dissertation research when he matriculated. He followed a pattern which is typical and which is encouraged for all of our Ph.D. students of exploring widely the available areas of research during his first two or three semesters.

In the first year of the program, a fellowship student typically takes four courses each semester. Mr. Raphael took a two-semester course in Analysis, which is taken by virtually all students in the program and which is a common denominator for research in most areas (probability, dynamical systems, numerical analysis, control, ...). He also took the two-semester sequence in Probability Theory, which is essential as preparation for research with our group. His other courses in the first year broadened his exposure to other areas of applied mathematics—Operations Research, Numerical Analysis, and Theory of Computation.

At the end of his first year, and during the summer, he started exploring research topics in speech processing.

3 Year II

The second year of the Ph.D. program is typically spent doing a combination of two things: (i) identifying clearer directions for dissertation research and deepening one's course background in those directions, and (ii) preparing for the Preliminary Exam, which is the turning point for admission to candidacy for the Ph.D.

Mr. Raphael focused his course work on a two-semester advanced sequence in Statistical Inference and Decision Theory and on a two-semester sequence in the Division of Engineering on Signal Processing and Pattern Recognition/Computer Vision. The inference and decision theory courses were well coordinated with the ones on signal processing and vision since they emphasized the use of the methods developed by our group using Markov Random Field models as a foundation for developing image processing algorithms.

During the summer after his second year, Mr. Raphael passed the Preliminary Exam with a major area of Probability and Mathematical Statistics, and minor areas of (1) Analysis and (2) Pattern Recognition. He was formally admitted to degree candidacy in July 1988.

4 Year III

Upon formal admission to candidacy, the focus of the degree program shifts to the dissertation research.

At the beginning of his third year, Mr. Raphael was testing his interests in two directions within our group. During most of the fall semester, he

worked with Professor Basilis Gidas, exploring the use of hidden Markov models for the description and analysis of various acoustic signals. At the same time, he was continuing to try to identify open questions in the general realm of mathematical methods for inverse problems such as ones occurring in computed tomography.

At the beginning of the Spring semester, he made a firm decision to work with Professor Donald McClure in the general area of mathematical methods for computed tomography. Mr. Raphael showed an extremely high degree of maturity and independence in his search for the right thesis problem. He was determined to identify his own problem, rather than have one handed to him. During the semester, he carefully considered open problems in the area of industrial computed tomography for nondestructive testing—specifically, new approaches to limited angle reconstructions and appropriate mathematical models for reconstructions of highly attenuating media. Late in the Spring semester, he settled on the problem which eventually became the focus of his research: the Radiation Therapy Treatment Planning Problem.

In planning his dissertation research, he was fortunate to have direct contact with medical researchers, physicists, and other mathematicians concerned with the formulation and analysis of Treatment Planning. He benefited especially from contacts with Allen Cormack and Todd Quinto at Tufts University. At the end of the fellowship period in August 1989, he had a firm plan for his dissertation and was well along the way towards carrying it out.

5 Dissertation Plan

The Radiation Therapy Treatment Planning Problem is closely related mathematically to the reconstruction problems of computed tomography—except it is not nearly so thoroughly studied and understood.

The central issue is easy to describe. A region of the body is to be exposed to radiation by directing one or more external beams of radiation toward the patient. The profile of the beams and the directions from which they are transmitted can be controlled by the therapist. The goal is to deliver a suitably high dose to a tumor, while sparing all other regions from damaging levels of radiation. The combination of beam sources and profiles is called a *treatment plan* and the variable map of radiation exposure with the patient is referred to as the *dose distribution*.

The mapping from the treatment plan to the dose distribution is a linear operator, the so-called *dose operator*. One knows ideally what dose distribution one wants to achieve. However, the dose distributions that are physically realizable are the strictly the ones associated with non-negative treatment plans. Almost never is the desired dose distribution physically realizable.

Mr. Raphael started his thesis research by trying to better understand and characterize the range and the null space of the dose operator. This is just a preliminary step to understanding ways in which algorithms might be designed in order to compute a physically realizable dose distribution and associated treatment plan which are as close as possible to the unrealizable ideal dose distribution.

The thrust of his research, however, will be on the formulation of clinically meaningful objective functions for quantifying how good or bad a given dose distribution is. A well-formulated objective function will make it possible to cast the problem of *computing* a treatment plan as an *optimization problem.* Then he will concentrate on the development and analysis of algorithms for optimization of the chosen objective function. The end goal will be to develop useful algorithms, together with an analytical understanding of what the algorithms actually do.

Mr. Raphael expects to complete his dissertation research early in the 1990-91 academic year. His research plan and progress to date is are consistent with this expectation.